Neutrino oscillations experiments

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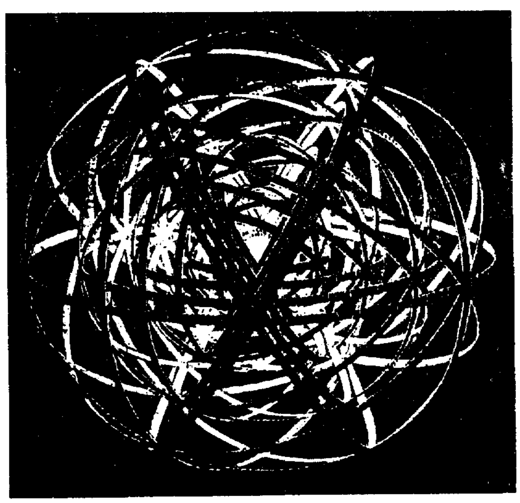

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NEUTRINO OSCILLATION EXPERIMENTS
Are oscillations really discovered?

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We have now three indications of neutrino oscillations. This paper presents the results obtained recently at accelerators, compares them with results from astrophysics and discusses the possible compatibilities. Perspectives in the field are sketched.

1 What are oscillations?

Neutrino oscillations were proposed almost thirty years ago.[1] Many experiments have looked for them and several have claimed their discovery. So, where are we today? Oscillations are spontaneous conversions between neutrinos of different flavours; they are a direct consequence of mixing. Classically the phenomenology has been developed on a 2-neutrino basis, arguing that it applies to the channel corresponding to the largest mixing.

It may be time to expand the phenomenology to the 3-neutrino system in order to understand the possible compatibility between some of the present results, and to outline the framework for a general analysis.[2] Here we limit ourselves to the three known neutrinos. To allow for more states would open a Pandora's box.

The 3 weak eigenstates are related to the 3 mass eigenstates through a CKM matrix:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Let us consider the oscillation between two physical neutrinos, for example ν_e and ν_μ. Several terms will participate:

$$P(\vec{\nu_e}\nu_\mu) = (a+b-c)U_{e1}^2U_{\mu 1}^2 + (a-b+c)U_{e2}^2U_{\mu 2}^2 + (-a+b+c)U_{e3}^2U_{\mu 3}^2 \,,$$

where $a = 2\sin^2(1.27\ R/E\ \delta m_{21}^2)$, and b and c have the same oscillatory pattern but with δm_{31}^2 and δm_{32}^2, respectively.

R is the distance between production and detection, and E the energy of the neutrinos.

If one of the three masses is large compared to the other two ($m_3 \gg m_1$, m_2) there will be one leading oscillation, and the probability becomes

$$P = 2\ c\ U_{e3}^2 U_{\mu 3}^2\ .$$

Thus there is the possibility of oscillation between ν_e and ν_μ which is an effect of m_3. This corresponds to a kind of indirect oscillation.

As a consequence, if the experiment is carried out at small distances, one can probe the oscillation which corresponds to the large δm^2 even though it may have a small mixing. On the other hand, the same physical channel can show the effect of a large mixing but at large distances when the small δm^2 has time to develop. In practice, this means that the solar neutrino deficit and the LSND result may test the same ν_e to ν_μ channel, one reflecting the small-mixing, large-δm^2 term, while the other (the Sun) reflects the large-mixing, small-δm^2 term.

2 Oscillation experiments

2.1 Disappearance or appearance?

How do we look for oscillations? Oscillation changes a neutrino ν into a different neutrino ν'. There are two complementary ways to detect a signal.

If the experiment is only sensitive to the original flavour present at production, the search consists in finding a decrease of the flux with distance, namely a disappearance of the initial flavour. This can be performed by either calculating the initial flux or using two detectors at two different distances and comparing the spectra. This method is not very precise since it relies on the subtraction of one large number from another. However, it is the method used at reactors, and it also applies to solar neutrinos.

The appearance method consists in looking for the new flavour absent in the original flux. The detector must be able to identify unambiguously the two different flavours. This method can be very sensitive since a single event of the new flavour is, in principle, enough to prove the oscillation. In practice, there are contaminations and backgrounds; however, the appearance method, which is used at accelerators, has proved to be very sensitive to test small mixings. But the distance/energy ratio is small, which explains why the accelerator results test relatively large δm^2.

2.2 Recent negative results

Four new results have been published recently.

- Charm2[3] looked for the ν_μ into ν_τ channel, extracting quasi-elastic ν_τ events with the τ decaying in the single-pion mode. The signature is clean because of the fine granularity of the detector. No excess is found.

- Karmen[4] at the ISIS spallation source did not find evidence for the ν_μ ν_e oscillation. The beam has a very characteristic time structure which allows a clean separation of initial neutrino flavour.

- CCFR[5] also searched for the ν_μ into ν_τ channel, studying the ratio NC/CC as a function of the total measured energy. An excess of ν_τ would give an increase in NC/CC.

- IHEP-JINR[6] has just published a limit on the disappearance of ν_e in a short neutrino beam enriched with ν_e (5%).

Figure 1 summarizes the negative results obtained so far in the three physical channels. Since the oscillation phenomenon is analysed as a function of two parameters [the mixing $\sin^2(2\Theta)$ and δm^2], the results appear as excluded regions in a 2-dimensional plot. A more general analysis is more difficult to visualize. For maximum mixing, the level of $\delta m^2 \simeq 10^{-2}$ eV^2 has been reached. This is already a good achievement considering that direct measurements of neutrino masses give the much poorer limits[7]:

$$m(\nu_e) \leq 3.4 \text{ eV}$$

$$m(\nu_\mu) \leq 170 \text{ keV}$$
$$m(\nu_\tau) \leq 24 \text{ MeV}$$

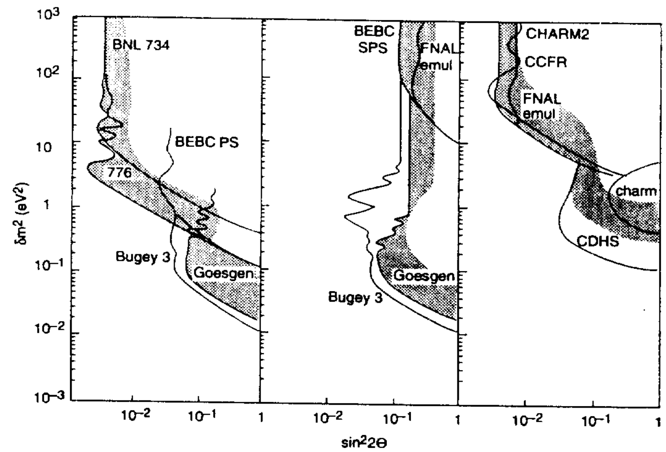

Figure 1: Present excluded regions in oscillation searches for the 3 physical channels.

3 Evidence of oscillations

Now for the more controversial results. We are faced with three different hints of possible oscillation discoveries. In order of seniority, they are:

3.1 Solar neutrinos

This problem has been with us for many years. The Sun produces an abundant flux of ν_e. Four experiments using different techniques have indeed detected ν_e but at a level significantly smaller than the calculated prediction.[8] At present, the most plausible interpretation of this deficit relies on the MSW effect, a resonant oscillation in the Sun interior. The solution gives a parameter $\delta m^2 \simeq 10^{-5}$ eV^2 and a mixing of order 1%.

3.2 Atmospheric neutrinos

From primary cosmic rays interacting in the atmosphere, a ratio of the order of 2 between ν_μ and ν_e is expected. Five underground experiments have published results and three of them, notably the Kamiokande experiment,[9] claim a disappearance of ν_μ. When interpreted by oscillation, the parameter δm^2 comes out to be about 10^{-2} eV^2 and the mixing is large.

3.3 LSND result

In 1995, the LSND experiment published a first result based on 9 events for a background of 2.1, claiming evidence for the oscillation ν_μ into ν_e with a probability[10]

$$P = (0.34 \pm 0.20 \pm 0.07)10^{-2} .$$

LSND consists of 167 tonnes of liquid scintillator observed by 1220 photomultipliers. The experiment detects the reaction

$$\nu_e + p \to e^+ + n$$

followed by a delayed 2.2 MeV γ ray from the capture $n + p \to d + \gamma$.

Very recently more data and an improved analysis have been published.[11] The excess is now statistically more meaningful with 22 events detected for a background of 4.6 events. This gives a probability of oscillation of

$$P = (0.31 \pm 0.10 \pm 0.05)10^{-2} .$$

3.4 Discussion

These three sets of data give us too many oscillations. Figure 2 shows the three preferred regions together with the excluded regions already displayed. Note that the LSND result is in contradiction with several other experiments except for a band at low δm^2.

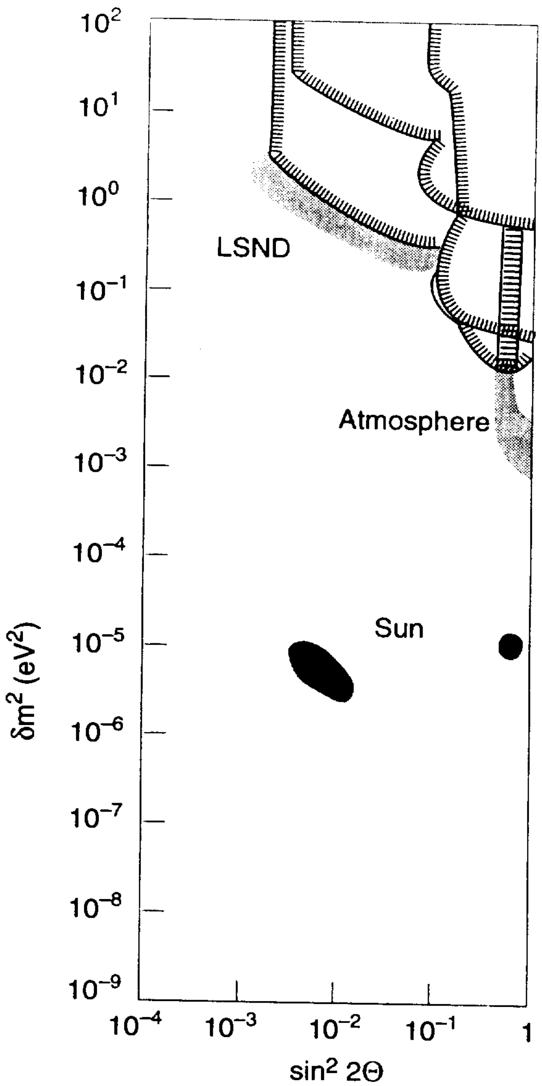

Figure 2: Preferred regions for the LSND, atmospheric and solar results. They do not necessarily apply to the same physical channel.

Clearly, the regions shown in Fig. 2 for the three sources of evidence do not overlap. Can we make sense out of such divergent information?

Assuming only three neutrinos with normal interactions and a hierarchy between the three masses as proposed by the see-saw mechanism, it is obvious that the three sources of evidence are incompatible.

If one trusts the solar neutrino result, the mass of the ν_μ is fixed at $m(\nu_\mu) \simeq 3 \times 10^{-3}$ eV, the mass of the ν_e being much smaller. But we have a choice for the ν_τ: $m(\nu_\tau) \simeq 0.1$ eV if one adopts the atmospheric hint; $m(\nu_\tau) \simeq 1$ eV if one prefers the LSND claim. Note that these two solutions are too small to give the ν_τ a cosmological *raison d'être.*

The experimental situation needs clarification.

4 Current experiments

Two experiments are currently taking data in the CERN high-energy neutrino beam. They are searching for the oscillation ν_μ into ν_τ in the mass region which is relevant for cosmology.

4.1 ν_τ as a dark matter candidate

The Big Bang model predicts the presence of fossil neutrinos in the entire volume of the Universe at a level of about 100 per cm^3 for each flavour. Astrophysicists observe an invisible mass in the Universe which could represent more than 90% of the total mass. It is tempting to relate these two facts. Assuming that the ν_τ is the heaviest of the three neutrinos, a 60-eV ν_τ would close the Universe. Present models of the missing mass prefer a mixture of hot and cold dark matter. This would favour a mass of 10–20 eV for the ν_τ.

Such a mass is extremely small for any direct measurement but is easily accessible by oscillations if the corresponding mixing is not too small. This is the justification for the two CERN experiments which are currently exploring the ν_μ ν_τ channel.

4.2 *The CERN experiments*

The experimental challenge is to identify a ν_τ interaction since the produced τ lepton travels only 1 mm before decaying. Two complementary approaches have been adopted.

- CHORUS uses a target made of emulsion. This is the ideal medium to examine the region around the interaction with high spatial resolution. Figure 3a shows one event with a short-lived particle reconstructed in the experiment. However, the target is passive and requires a sophisticated spectrometer to enrich the sample of data to be scanned.

- NOMAD is a complete spectrometer with a light target inside a magnetic volume, able to measure as precisely as possible and identify particles in order to apply kinematical cuts to extract a signal. Figure 3b shows a reconstructed K^0 mass obtained from the data.

Both experiments hope to reach a limit of a few 10^{-4} in mixing for δm^2 above 30 eV^2.

5 Perspectives

5.1 *Basic rules of oscillation searches*

In order to explore smaller mixings, an experiment must increase its statistics and control its systematical uncertainties. In the case of no background the limit on mixing decreases linearly with the statistics. In going to smaller δm^2, the statistics play little role. The limit on δm^2 depends primarily on the parameter distance $\div$ energy, and small δm^2 are reached at large distances and/or small energies. This explains the present plans with regard to oscillation searches.

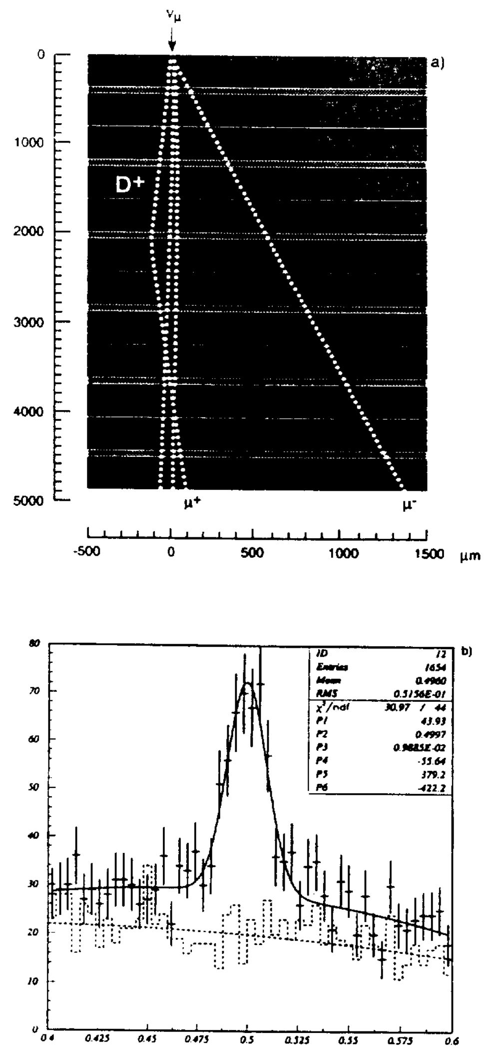

Figure 3: (a) One event with a short-lived particle reconstructed in the emulsion of the CHORUS detector; (b) K^0 signal reconstructed in the NOMAD target.

5.2 Experiments, projects and dreams

LSND will continue to take data for two more years, as will Karmen, which has improved its veto system. CHORUS and NOMAD have runs scheduled until the end of 1997.

In parallel there are two long-distance reactor experiments (Chooz and San Onofre) with detection at 1 km, which will start taking data this year. They should cover the region of the atmospheric anomaly.

In the more distant future long base-line searches are projected. A 1-GeV ν_μ beam from KEK should cross the Superkamiokande detector, 250 km away, in 1999. Around 2002 the Cosmos experiment should improve on the ν_μ ν_τ mixing down to a few 10^{-5}, and at the same time the beam from Fermilab should hit a detector in the Soudan mine 730 km away. The same distance can be explored with the Icarus detector under the Gran Sasso laboratory and a beam from CERN.

In 10 years from now, the excluded regions may extend down to 10^{-5} in $\sin^2 2\Theta$ and 10^{-3} in δm^2 or better, but the *terra incognita* may still look as vast as it does today.

Neutrinos are mysterious particles. Many questions concerning their nature remain unanswered, and experimental puzzles regularly arise. Let us hope that oscillations will be firmly discovered before long.

References

1. B. Pontecorvo, Sov. Phys.-JETP **26**, 984 (1968).
2. C.W. Kim and H. Nishiura, Preprint JHU–HET 8506 (1985);
   K.S. Bahn, et al. *Phys. Lett.* **B359**, 351 (1995);
   S.M. Bilenky et al., *Phys. Lett.* **356**, 273 (1995).
3. M. Gruwe et al., *Phys. Lett.* **B309**, 463 (1993).
4. B. Armbruster et al., *Nucl. Phys.* **B38**, 235 (1995).
5. K.S. McFarland et al., Preprint FNAL–PUB–95/153.
6. A.A. Borisov et al., *Phys. Lett.* **B369**, 39 (1996).
7. See for example J. Bonn in *Proc. 8th Rencontres de Blois: Neutrinos, Dark Matter and the Universe,* Blois, France, 1996 (to be published).

8. GALLEX Collaboration, *Phys. Lett.* **B327**, 377 (1994);
SAGE Collaboration, *Phys. Lett.* **B328**, 234 (1994);
Homestake Collaboration, *Nucl. Phys.* **B38**, 47 (1995);
Kamiokande Collaboration, *Nucl. Phys.* **B38**, 55 (1995).
9. K.S. Hirata et al., *Phys. Lett.* **B280**, 146 (1992).
10. C. Athanassopoulos et al., *Phys. Rev. Lett.* **75**, 2650 (1995).
11. C. Athanassopoulos et al., Preprint LA-UR-96-1326.